

Micro-CHP systems for residential applications

Michel De Paepe ^{a,*}, Peter D’Herdt ^a, David Mertens ^b

^a Department of Flow, Heat and Combustion Mechanics, Ghent University—UGent, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

^b Cogen Vlaanderen, Zwarte Zustersstraat 16 bus 9, B-3000 Leuven, Belgium

Received 15 July 2005; received in revised form 24 December 2005; accepted 24 December 2005

Available online 28 February 2006

Abstract

Micro-CHP systems are now emerging on the market. In this paper, a thorough analysis is made of the operational parameters of 3 types of micro-CHP systems for residential use. Two types of houses (detached and terraced) are compared with a two storey apartment.

For each building type, the energy demands for electricity and heat are dynamically determined. Using these load profiles, several CHP systems are designed for each building type. Data were obtained for two commercially available gas engines, two Stirling engines and a fuel cell.

Using a dynamic simulation, including start up times, these five system types are compared to the separate energy system of a natural gas boiler and buying electricity from the grid.

All CHP systems, if well sized, result in a reduction of primary energy use, though different technologies have very different impacts. Gas engines seem to have the best performance. The economic analysis shows that fuel cells are still too expensive and that even the gas engines only have a small internal rate of return (<5%), and this only occurs in favourable economic circumstances.

It can, therefore, be concluded that although the different technologies are technically mature, installation costs should at least be reduced by 50% before CHP systems become interesting for residential use. Condensing gas boilers, now very popular in new homes, prove to be economically more interesting and also have a modest effect on primary energy consumption.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Combined heat and power (CHP); Residential; Gas engine; Stirling engine; Fuel cell

1. Introduction

The concept of combined heat and power (CHP) or cogeneration has been known for a long time. The idea of using waste heat coming from a heat engine for heating purposes has many times been successfully implemented in industry.

* Corresponding author. Tel.: +32 9 264 32 94; fax: +32 9 264 35 75.

E-mail address: michel.depaepe@UGent.be (M. De Paepe).

Nomenclature

P_E	electrical power (W)
P_T	thermal power (W)
η_E	electrical efficiency (–)
η_T	thermal efficiency (–)

Because of the growing environmental awareness and the ratification of the Kyoto Protocol, combined heat and power receives again more attention as a way to contribute to the reduction of energy use and emissions [1].

A large amount of energy in the world is used for building heating [2]. Most buildings in Western Europe are heated with a central heating system using natural gas or a fuel oil fired furnace. The efficiency of these furnaces has increased a lot in the last few years, especially through the introduction of condensing units. A next step could be to replace these furnaces by a CHP unit, not only providing heat to the building, but also electrical power. In the recently published Energy Performance of Buildings Directive of the EU, CHP is considered a means to fulfill the energy requirements of buildings. For office buildings and multi-storey buildings, a lot of cases have been reported, e.g. in Refs. [3,4].

At the moment, new technologies are emerging on the market, having a promising prospect for the near future [5], providing CHP for small buildings, as houses and small apartments. Because of the novelty of the technology in this field of application, operational experience is not available over extended periods.

In the past, few studies focusing on CHP for residential applications were found. Bernotat and Sandberg [6] reported on the possibilities of using CHP for clustered dwellings in Sweden and the Baltic states, concluding that small scale CHP has high perspectives if the total heat demand in an area is high enough.

Recently, Dentice d'Accadia et al. [7] reported on the possibilities of residential micro-CHP systems. They present a general survey of market and technological perspective. An energy analysis is presented of some domestic appliances and a test facility for micro-CHP modules is described. The authors conclude that future introduction of micro-CHP for domestic applications will be subject to available technology, matching of electrical and thermal load profiles and gas and electricity prices.

A demonstration project was reported with a fuel cell in Ref. [8]. The experiments were aimed at assessing the suitability of this kind of system to supply Italian residential customers. Factors such as performance, flexibility and operational requirements were evaluated under all possible operating conditions, both under grid connected and stand alone configurations. The results show that the prototype behaved as expected for a first “proof of concept” system and outlined improvements to be achieved in order to satisfy the energy needs of small residential applications.

Voorspools and D'haeseleer [9] analysed the response of a gas engine cogeneration unit in a house to a certain heat demand. It was shown that an engine is rather slow in response for heating, whereas the electric transient is negligible. These authors also performed several dynamic simulations to quantify the impact of massive installation of small cogeneration units in houses. The possible negative aspects of cogeneration on commissioning of new plants are discussed. The importance of long annual operating time is also indicated.

2. Methodology and scope

2.1. CHP technology

In this paper, five micro-CHP systems (<5 kW) are evaluated for use in residential applications by taking the viewpoint of a detached single family house (reference case). Comparison is made with a terraced house and a two storey apartment.

First, the load profiles for heat and electricity demand are determined for a four person family (2 adults and 2 children). This was done using DOE 2.5 and running a whole year simulation for the test reference ear of Belgium [10].

Table 1
Power and efficiency of CHP technologies

CHP	P_E (kW)	η_E (%)	P_T (kW)	η_T (%)
Senertec	5.5	27	12.5	61
Ecopower	4.7	25	12.5	65
Solo	2–9.5	24	8–26	72
Whispertech	1	12	4.9–8	80
Idatech	4	25	9	55

The requisite data for the simulation include: building dimensions, building materials, installed equipment and lighting, usage time profiles (schedules), data concerning the heating system and the ventilation rates. These data were obtained from the building plans and the building file and by questioning the users of the building.

The calculated energy use profiles were then used to dimension the CHP and to assess the building performances when CHP is used. The studied CHP technologies are (Table 1):

- Two gas engines running on natural gas:
 - Dachs HKA F 5.5 (Senertec) [11].
 - Mini-BHKW (Ecopower) [12].
- Two Stirling engines, which are external combustion engines. The hot part of the engine can be introduced into a furnace. The primary advantages of the Stirling engine are the freedom of choosing the fuel and the easiness to install the engine in a boiler; the disadvantage is the rather small electrical efficiency. Two commercial small scale systems were found:
 - Stirling 161 microKWK module (Solo) [13].
 - Whispergen (Whispertech) [14].
- An Idatech fuel cell running on hydrogen gas with reforming of natural gas [15].

2.2. Primary energy

For each configuration, the primary energy savings, CO₂ emission reduction and the financial savings are calculated. To assess the primary energy savings and CO₂ emission reduction, comparison is made with the separate production of heat and electricity. For heating, a boiler with 90% efficiency is considered. Electricity is bought from the grid. The amount of primary energy needed to produce this electricity is strongly dependent on the technology that is used. Three different scenarios (typical for Belgium) will be considered:

- The electricity is produced by a combined cycle gas/steam turbine plant. A combined cycle plant has a typical efficiency between 53 and 56%. However, considering the transformation and transport losses, a realistic assumption for the actual efficiency would be 50%.
- The electricity is produced by an average fossil fuel power plant: next to the combined cycle plants, coal fired plants are also taken into consideration. The calculated average efficiency of the Belgian fossil fuel plants is 42%.
- The electricity is produced by the average Belgian power plant. Because, in Belgium, nuclear energy is the primary source of electricity production, an average efficiency of 37% is obtained.

For the CHP scenarios, the running strategy is determined by the heat demand. Surplus electricity is delivered to the grid. If more electricity is needed than the CHP unit delivers at a certain moment in time, this extra amount of electricity will be bought from the grid. To calculate the primary energy use, the electricity sold to the grid is deducted from the total amount used, using the central power plant efficiency, because this electricity has not been produced by the central power plant. The CHP systems can never completely replace the

boiler ($32 \text{ kW}_{\text{th}}$). Therefore, a back up boiler ($\eta = 90\%$) will provide extra heating when the thermal energy demand exceeds the maximum power. It is to note that gas engines have limited part load behaviour. This is not the case for Stirling engines. Therefore, in the case of gas engines, the back up boiler will take over, providing all the heat as soon as the gas engine runs at less than 50% load. In addition, the efficiency is corrected as a function of the load of the engine. Finally, comparison is made with buying electricity from the grid and heating by a condensing boiler with 107% efficiency.

2.3. CO_2 emissions

In the reference situation, without CHP, a certain amount of CO_2 is produced through the generation of heat and electricity. The produced CO_2 through the generation of heat is for a gas boiler, assumed to be 56.1 g CO_2 per MJ of natural gas burned.

The CO_2 produced through electricity generation is strongly dependent on the technology that produces this electricity. For the three different scenarios, this is:

- Electricity is produced by a combined cycle power plant with efficiency 50%. As natural gas is the energy source of a power plant, there is 56.1 g of CO_2 produced for every MJ of natural gas used.
- Electricity is produced by an average fossil fired power plant. Looking at the average performance of Belgian fossil fired power plants, 617 g of CO_2 is emitted per kW h of electricity consumption at the house [16].
- Electricity is produced by the average Belgian power plant: the CO_2 emission of the average Belgian power plant equals 272 g of CO_2 per kW h of electricity due to the high share of nuclear power (55%) in Belgian power production [16].

For the efficiencies and CO_2 production of the respective CHP technologies, the same assumptions as above can be made. The efficiencies allow calculating the necessary amount of produced energy and, while the gas engines and Stirling engines both use natural gas as energy source, the same figure (56.1 g/MJ) as above can be used. For the fuel cells, it is assumed that no CO_2 is produced during the process. However, during the production of the H_2 for the fuel cells (the reforming reaction), a certain amount of CO_2 is produced. The efficiency of this reforming reaction is also taken into account in the efficiency of the fuel cell. Assuming that natural gas is used to produce the hydrogen in the fuel cells, one can consider 56.1 g/MJ as being the correct figure to use in fuel cells, too.

3. Building data

3.1. Building dimensions

The detached house consists of three floors. The length amounts to 14 m , while the width equals between 9.4 m and 11.3 m . The building has a maximal height of 8.5 m . Some slight simplifications were made because of the lack of flexibility of DOE in simulating non-rectangular forms. The simplified version, as simulated, of the house is, in a very schematic way, shown in Fig. 1. The detached house was built according to the Belgian building directive for insulation values [17].

The terraced family house also consists of three floors. The length (the part of the house that touches the adjacent houses) equals 18.78 m , while the width equals between 5.83 m and 2.63 m . The simplified version of the building is schematically shown in Fig. 1. For the second house, only a little material information was available, so the same U values were chosen and used in the simulation as for the base case. Only for the windows, which were known to have single pane glass, another U value was used.

The double apartment is attached to other apartments at the top, the bottom, the east side and the west side. As this type of building (-part) houses two families, the use of electricity and domestic hot water (DHW) will have to be taken into consideration for both families.

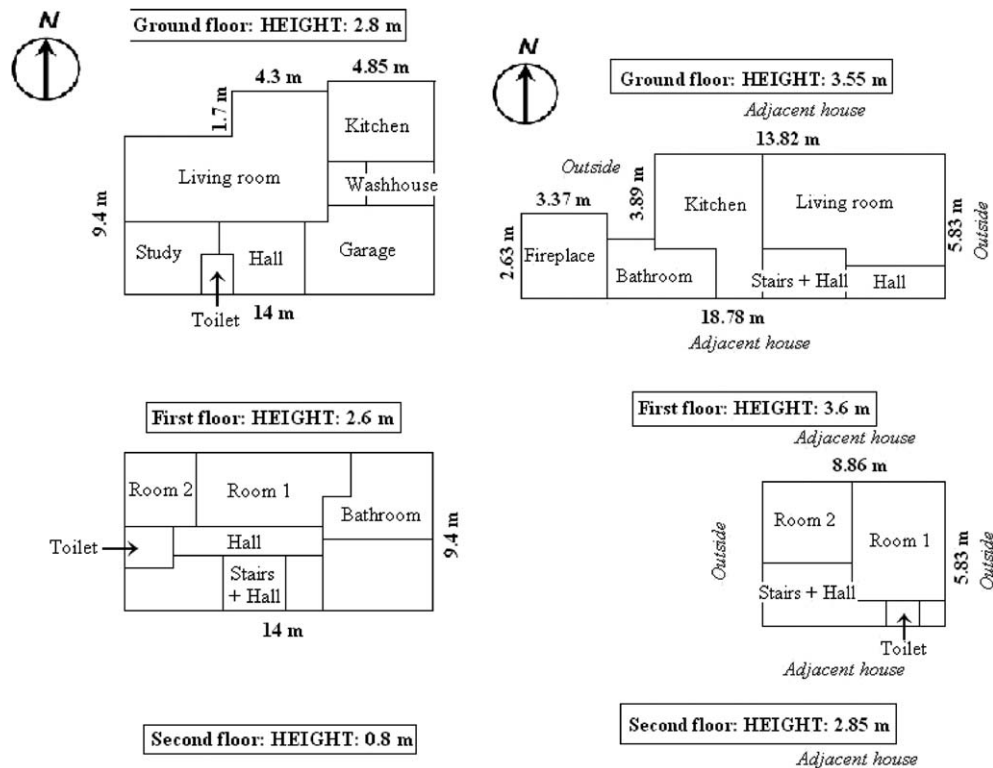


Fig. 1. Detached (left) and terraced (right) house.

3.2. Electrical equipment and lighting

For each room in the houses, the installed equipment and lighting power were listed. For the simulation, usage patterns were introduced for light and equipment that were obtained by asking the inhabitants or by making realistic assumptions.

The houses are equipped with a central heating system with a classical boiler with efficiency of 90%. It is important to note here that the efficiency of the boiler does not influence the actual heat demand of the building. This is only influenced by the transmission and ventilation losses (set to 0.5 ACH), internal and solar heat gains and the efficiency of the distribution system. The efficiency of the boiler itself will only influence the final primary energy demand.

Temperature demands are highly dependent on the users of the building. The central heating system is controlled by an on/off thermostat with time programming. The actual thermostat settings are given in Table 2. It is to note that during the summer months (June–September), there's considered to be no heating necessary and the mentioned thermostat settings are, therefore, only valid in the other months.

The boiler is also supplying domestic hot water (DHW). The main spots where DHW is taken are the bathroom (shower, bath tub and sink) and the kitchen (kitchen sink).

Table 2
Thermostat settings

Heating	On (>21 °C)	Off (>12 °C)	On (>21 °C)	Off (>12 °C)
Week days	6 a.m.	8 a.m.	5 p.m.	10 p.m.
Weekend	7 a.m.			10 p.m.

4. Energy saving and CO₂ reduction

4.1. Detached house

The simulating process results in the following data concerning the energy demands of the family in the reference situation:

- Total electricity demand: 3.61 MW h.
- Total primary energy use for heating: 34.19 MW h.

The results for the primary energy consumption of the different CHP units, in relation to the reference case with a gas fired combined cycle power plant, are shown in Fig. 2.

As can be seen, the largest savings for primary energy use are obtained using the Solo Stirling engine. The savings when using a condensing boiler are also significant, being higher than the Whispertech Stirling engine and the fuel cell.

As mentioned before, these calculations are done, taking into account the electricity that is produced by the CHP both for proper use and for delivery to the grid. Only a small part (some 10–15%) of the electricity generated by the CHP is used for proper use. In Table 3, the effect of different central power plant systems is shown. If the central power plant is less efficient, savings rise, as is expected.

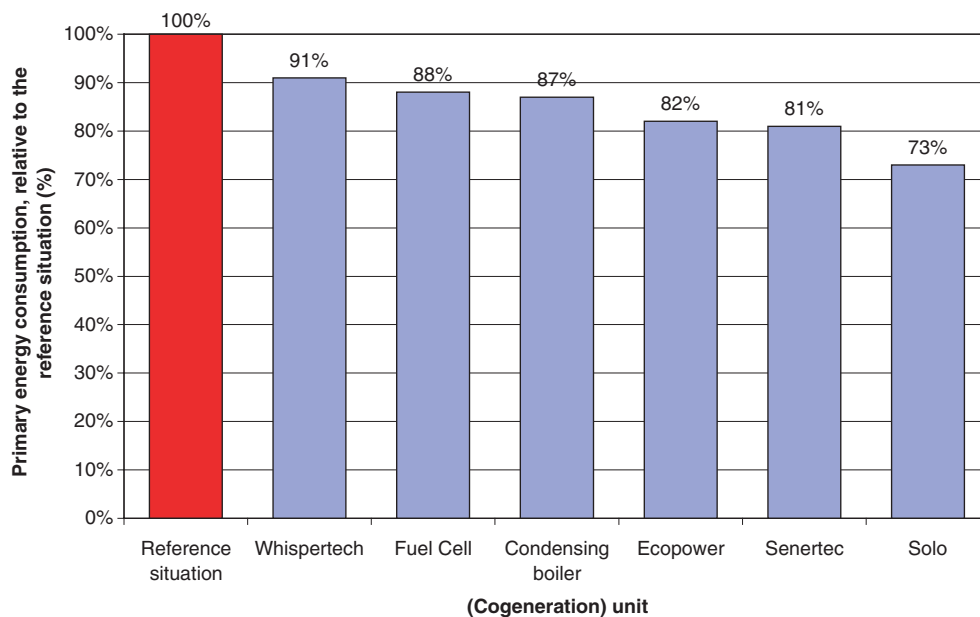


Fig. 2. Primary energy consumption for different CHP units.

Table 3

Relative primary energy savings for different CHP units compared to different central power plants

	Combined cycle power plant (%)	Average fossil power plant (%)	Average Belgian power plant (%)
Senertec	19.3	27.9	34.7
Ecopower	18.5	25.9	31.6
Whispergen	8.9	11.7	13.9
Solo Stirling	26.8	34.7	41.0
Fuel cell	12.0	21.7	29.3

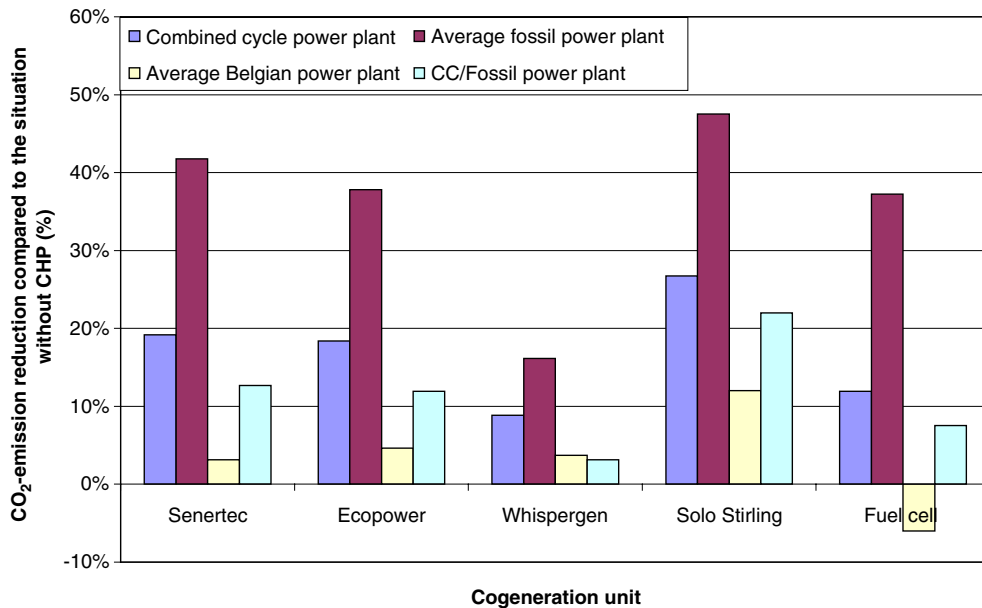


Fig. 3. Relative CO₂ reduction for different CHP types.

The results for CO₂ production are obviously quite the same as the results for the primary energy use for the scenario of the combined cycle power plant, as can be seen in Fig. 3. It is again the Solo Stirling engine that has the best results. The reductions vary between –6% (for the case of the fuel cell and the average Belgian plant, which is negative because of the relatively low performance of the fuel cell in comparison to the other technologies) and 48%. However, the largest reductions are now obtained in the scenario with the average fossil fired power plant scenario because of the high CO₂ production for that type of central plant. Dynamic simulations could lead towards different power plant types for, on one hand, the avoided plant when the CHP operates and, on the other hand, the back up plant providing electricity for the house when the CHP does not operate. An example of this for which the avoided plant is a combined cycle power plant and the back up plant is the average fossil power plant is also shown in Fig. 3. Emission reductions tend to be lower in this case than in the case with the combined cycle power plant as a reference, as was also concluded in Ref. [9].

4.2. Terraced house—2 storey apartment

The simulating process results in the following data concerning the energy demands of the terraced house in the reference situation:

- Total primary energy use for heating: 27.19 MW h.
- Total electricity demand: 2.87 MW h.

and for the 2 storey apartment:

- Total primary energy use for heating: 31.3 MW h.
- Total electricity demand: 5.63 MW h.

The results for these types of houses are similar to the results of the detached house. To illustrate this, the relative primary energy savings for the Senertec gas engine for all scenarios are compared for all three types of houses in Fig. 4.

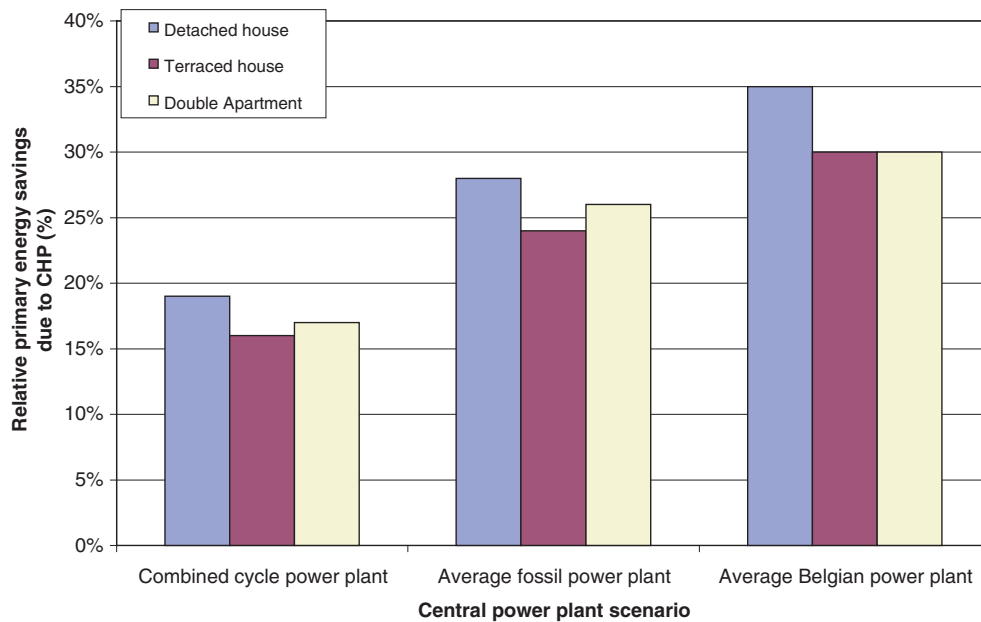


Fig. 4. Relative primary energy savings for detached house, terraced house and two storey apartment for a Senertec gas engine compared to different central power plant scenarios.

4.3. Building insulation level

The insulation level of the building strongly influences the heat demand. Four cases are studied for the detached house:

- MINMIN: very bad insulation, especially for windows.
- MIN: the, in Belgium, legally allowed maximum U values for all the building materials (for windows even worse).
- BASE: the U values of the building materials used in the actual house.
- MAX: U values of building materials that could be reasonably used in a new building.
- MAXMAX: U values of building materials that are considered the lowest (and most expensive) economically justified use.

The calculated relative primary energy savings, using the Ecopower technology and with reference electricity production by a combined cycle power plant are shown in Fig. 5 as a function of the total energy use in the reference situation. The energy use is higher when the insulation is lower. As can be seen, the extent of the insulation has little or no effect on the possible relative energy savings due to CHP. Of course, the annual heat demand and absolute energy savings will be lower. This tendency is also observed for other technologies and other scenarios.

4.4. Variation of the electricity use

It can be stated that the owners of the detached house use a lot of electricity. The effect of installing less lighting power was analysed. The house is simulated, therefore, with relighting in a sustainable manner with high performance lamps and assuring a minimal lighting level necessary in a residence. The influence on the relative primary energy savings is shown for the Ecopower technology and the different plant scenarios in Fig. 6.

As the energy production and, therefore, also absolute primary energy savings of the CHP installation only depend on the heat demand, and the primary energy consumption for the reference situation decreases when

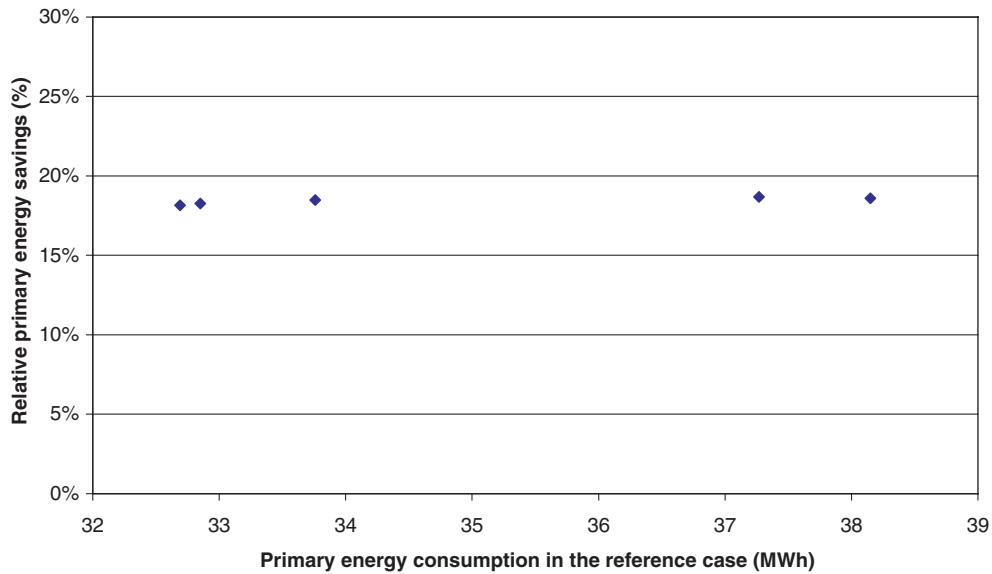


Fig. 5. Relative primary energy savings as function of the primary energy use in the reference case.

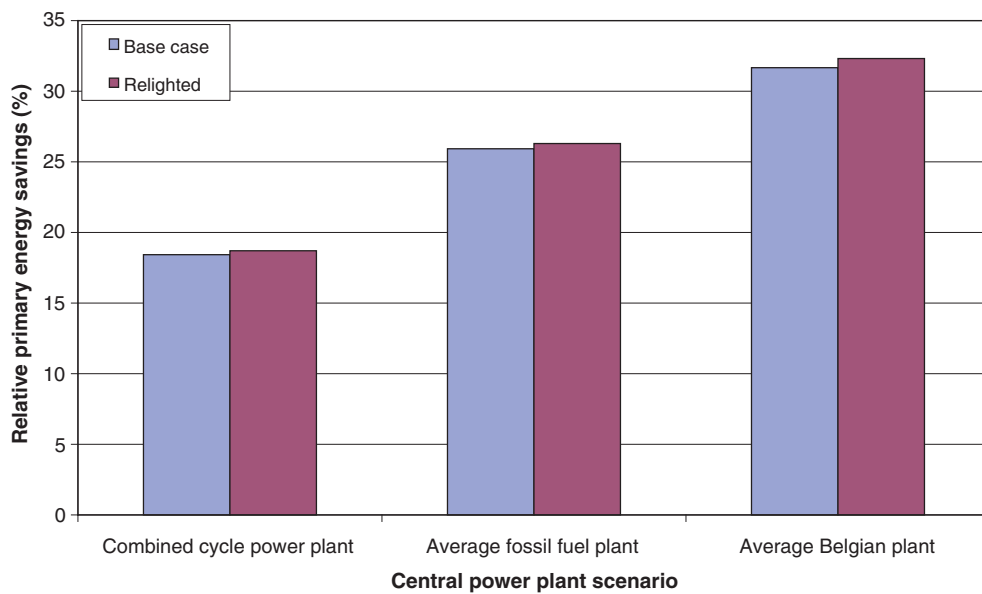


Fig. 6. Comparison of the relative primary energy savings (Ecopower gas engine) for the base case and the relighted case.

the electricity demand of the house decreases, the primary energy savings will rise. Fig. 7 illustrates this, showing slightly higher relative primary energy savings when the house is relighted.

5. Economics

5.1. Investment and maintenance costs

The investment cost for and maintenance costs of the studied CHP technologies and the condensing boiler can be found in Table 4.

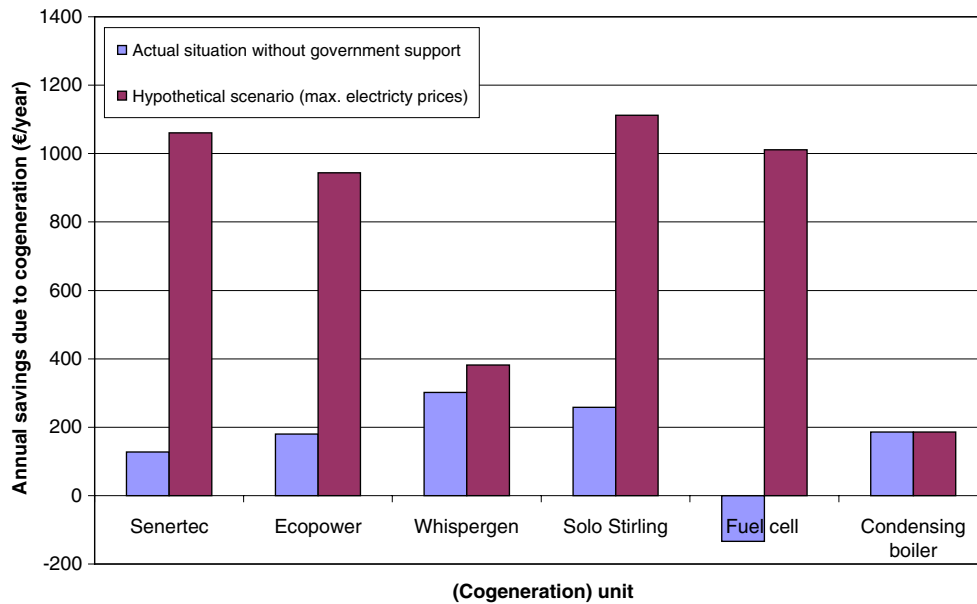


Fig. 7. Annual savings.

Table 4
Investment and maintenance costs

	Installation cost (€)	Maintenance costs (€/y)
Senertec	13,750	100
Ecopower	11,750	100
Solo	25,000	75
Whispertech	9000	75
Idatech	140,000	35
Condensing boiler	2000	35

5.2. Electricity prices

The actual situation in Flanders, including actual gas and electricity prices for residential customers, was used for the financial calculations. For small scale electricity generation ($<10 \text{ kW}_e$), meters may count backwards. Thus, only net annual production is considered to be put on the grid. This means synchronism between electricity production by the CHP and electricity consumption in the house is not required. Up to an amount of electricity equalling the annual electricity demand of the house, the value of electricity produced by the CHP is the avoided cost for purchasing electricity. The remaining amount of produced electricity, being put on the grid, has, of course, a lower value. As the energy market is liberalised in Flanders, the value of this amount of electricity is the price a power supplier wants to pay for it. An overview of purchasing prices and selling prices is given in Table 5. As can be seen, the situation in which the customer has chosen two electricity pay rates (day and night rate) are assumed.

Table 5
Energy prices for buying and selling

	Gas (c€/MJ)	Electricity—day rate (c€/kW h)	Electricity—night rate (c€/kW h)
Purchasing	0.954875	15,560.061	8370.061
Selling	—	2.25	2.25

5.3. Annual profits

The annual profits are the sum of:

- The *avoided costs* for purchasing electricity, equalling the purchasing price shown in Table 5.
- The money received for the electricity which is *sold to the grid*.

These profits are decreased with

- The *maintenance costs*.
- The *extra cost* due to the extra amount of *gas* used.

In the case of the condensing boiler, the annual profits consist only of the avoided costs for gas, as the condensing boiler has a higher efficiency than the reference boiler.

The annual financial savings through the use of CHP are shown in Fig. 7. Also, a comparison is made with the hypothetical situation in which all produced electricity can be valorised at the maximal (purchasing) price.

For most CHP technologies, the annual savings in the actual situation turn out to be low, which is primarily due to the fact that the largest part (85–90%) of the produced energy is sold to the grid at very low prices. In fact, the family can be seen as a small electricity producer, which is very poorly paid. This makes the annual savings too low to return the investment cost in a reasonable amount of time.

In the hypothetical situation of a meter also counting backwards in the case of net annual production of electricity, the annual savings rise a lot. Only for the Whispergen, are the rises rather small. This is because the annual electricity production of a Whispergen does not differ that much from the annual electricity demand, avoiding high amounts of electricity having to be sold to the grid. The condensing boiler seems to have the lowest annual savings of all the studied technologies.

6. Conclusions

New micro-CHP technologies are emerging on the market. Five different types were studied in this paper. It is to notice that the electricity production of the CHP units is about 90% delivered to the grid. Only 10% is used by the households. From the primary energy saving and CO₂ reduction point of view all CHP installations when operated on heat demand lead to a reduction. Stirling engines have the best possibilities. Using a condensing boiler is often as good as installing a CHP plant.

From the financial point of view, installing CHP in a household is not interesting, as investments are high and return is low. Only if a backward counting meter can always be used, can the technologies become profitable. Again, this is caused by the high quantities of electricity being sold to the grid.

References

- [1] Rolfsman B. CO₂ emission consequences of energy measures in buildings. *Build Environ* 2002;37:1421–30.
- [2] Pilavachi PA. Mini- and micro-gas turbines for combined heat and power. *Appl Therm Eng* 2002;22:2003–14.
- [3] Smith MA, Few PC, Twidell JW. Technical and operational performance of a small scale, combined heat-and-power (CHP) plant. *Energy* 1995;20:1205–14.
- [4] Evans R. Environmental and economic implications of small-scale CHP. *Energy Policy* 1993;21:79–91.
- [5] Alanne K, Saari A. Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. *Renew Sustain Energy Rev* 2004;8:4001–31.
- [6] Bernotat K, Sandberg T. Biomass fired small-scale CHP in Sweden and the Baltic states: a case study on the potential of clustered dwellings. *Biomass Bioenergy* 2004;27:521–30.
- [7] Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli L. Micro-combined heat and power in residential and light commercial applications. *Appl Therm Eng* 2003;23:1247–59.
- [8] Gigliucci G, Petrucci L, Cerelli E, Garzisi A, La Mendola A. Demonstration of a residential CHP system based on PEM fuel cells. *J Power Sources* 2004;131:62–8.
- [9] Voorspools K, D'haeseleer W. The evaluation of small cogeneration for residential heating. *Int J Energy Res* 2002;26:1175–90.
- [10] NN European communities. Test reference years, TRY, Directorate General XII for Science, Research and Development, 1985.

- [11] <http://www.senertec.de>.
- [12] <http://www.ecopower.de>.
- [13] <http://www.stirling-engine.de>.
- [14] <http://www.whispertech.co.nz>.
- [15] <http://www.idatech.com>.
- [16] NN, Decree on minimal insulation standards for buildings, 18/09/1991—Belgisch Staatsblad van 18/3/1992 [in Dutch].
- [17] NN Statistics of the year 2004 of the electricity sector, 2005 [in Dutch].